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WETTED-REGION STRUCTURE IN HORIZONTAL UNSATURATED FRACTURES: WATER ENTRY THROUGH THE SURROUNDING POROUS MATRIX

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ABSTRACT

Small-scale processes that influence wetted structure within the plane of a horizontal fracture as the fracture wets or drains through the matrix are investigated. Our approach integrates both aperture-scale modeling and physical experimentation. Several types of aperture-scale models have been defined and implemented. A series of physical experimental systems that allow us to measure wetted-region structure as a function of system parameters and water pressure head in analogue fractures also have been designed. In our preliminary proof-of-concept experiment, hysteresis is clearly evident in the measured saturation/pressure relation, as is the process of air entrapment, which causes a reduction in the connected areas between blocks and the wetted region available for flow in the plane of the fracture. A percolation threshold where the system is quickly spanned, allowing fluid conduction in the fracture plane, is observed which is analogous to that found in the aperture-scale models. A fractal wetted and entrapped-region structure is suggested by both experiment and modeling. This structure implies that flow tortuosity for both flow in the fracture and for inter-block fluid transfer is a scale-dependent function of pressure head.

INTRODUCTION

The U.S. Department of Energy is investigating a prospective site for a high-level nuclear waste repository located in unsaturated volcanic ash (tuff) deposits hundreds of meters thick at Yucca Mountain, Nevada. Research directed toward understanding water flow and radionuclide transport in unsaturated, fractured rock has been reviewed in a number of papers.[1,2,3] Current conceptual models of unsaturated flow within fractured rock are of undetermined validity. Many assumptions inherent in the flow and transport process models and in the choice of properties used in these models have yet to be tested through physical experimentation.

In support of flow and transport model development and validation, a research program has been developed at Sandia National Laboratories for the Yucca Mountain Site Characterization Project to investigate mechanisms and processes that govern flow and transport through unsaturated, fractured rock.[4,5,6] The research program integrates fundamental physical experimentation with conceptual model formulation and mathematical modeling.

One area of high-priority research is the definition of effective large-scale properties for heterogeneous fractured media, including fracture/matrix interaction. As part of this research, the effect of fracture wetted-region structure on fracture hydraulic properties and fracture/matrix interaction must be understood so that valid simplifications can be formulated and incorporated into current models. This paper covers a portion of this research concerning wetted-region structure in horizontal, unsaturated fractures where the entry and exit of water occur through the matrix.

In this paper we define the research problem and describe our investigative approach, which encompasses both aperture-scale modeling and systematic physical experimentation. We describe several aperture-scale models that yield wetted structure and a series of analogue fracture/matrix systems designed for systematic physical experimentation. For proof-of-concept purposes, a preliminary experiment was conducted. The results of the preliminary experiment in combination with those from general aperture-scale models reported in the literature yield implications for fracture permeability, inter-block communication and the definition of effective-media properties. These implications and their validity must be addressed by future research in this area.

PROBLEM DEFINITION

In order to develop and validate models for flow and transport through unsaturated fractured rock formations, we must first understand flow at smaller scales and the behavior of small-scale hydrologic processes. Understanding these small-scale processes is necessary to define effective-media properties, e.g., hydraulic conductivity, moisture release, and dispersivity relations for fractured rock masses.

Fractured blocks may be broken down conceptually into a fracture network and a matrix network. In each of these networks, questions concerning property definition, variability, and connectivity are paramount. In addition, fracture/matrix interaction --- the complex interaction between the two networks as a function of pressure in steady-state problems and as a function of time and pressure in transient problems --- must be understood in order to model large-scale hydraulic behavior in a valid manner.

Most analyses and experiments to date have assumed a uniform wetted structure within the fracture regardless of the orientation of the fracture with respect to gravity or the mechanism of imbibition.[7,8] There is ample evidence, however, that fracture wetted structure will not be uniform for any of these cases.[4,5,9]

What will be the effects of a non-uniform wetted-structure within a fracture? The effects depend on the structure that forms. For example, if air entrapment occurs at a small scale everywhere in a fracture, its effect on both inter-block flow/transport tortuosity and within-plane fracture flow/transport tortuosity (thus hydraulic permeability and dispersivity) will be slight. However, if a fractal distribution of entrapped regions occurs, as is suggested by simple percolation theory, it will affect tortuosity for both these processes greatly.

Here we consider the problem of fracture wetted structure where water is supplied to a horizontal fracture through the matrix at very low flow rates (quasi-static limit). At this stage, situations in which flow dynamics are important (i.e., where flow rate is not slow relative to the saturated permeability of the matrix) are not considered.

We first address two questions:

(1) What is the structure of the wetted region in the plane of a horizontal fracture as a function of system parameters and water pressure?
(2) Can the wetted-structure and wetting process be modeled by aperture-scale models that embody capillary laws?

Answering these two questions will yield information required for defining effective-media properties for fractured blocks, such as hysteretic inter-block connectivity functions, bounds on flow tortuosity for both inter-block fluid transfer and in-plane fracture flow (hydraulic permeability and solute dispersion effects), and the onset of flow through an unsaturated fracture (pressure at which wetted structure spans a fracture at the scale of the problem).

INVESTIGATIVE APPROACH

Our investigative approach combines numerical aperture-scale modeling and systematic physical experimentation to characterize wetted-region structure as a function of system variables and parameters. A full list of system parameters, boundary conditions, and initial conditions is given in Table 1. While we plan a systematic study of most of the system parameters, we will first concentrate on the physical properties of the fracture.

The various aperture-scale models introduced below will be investigated to determine their behavior as a function of aperture distribution and spatial structure. Physical experiments will be conducted to do likewise. Comparison of numerical simulation and physical experiments will allow us to determine which model characterizes wetted structure correctly as a function of aperture field, pressure, and scale. Once this model validation has been accomplished, the numerical solution will be exercised to address questions imperative for the valid definition of effective media properties in unsaturated fractured rock formations.

Aperture-Scale Numerical Modeling

Several modeling approaches, all adaptations of the standard percolation model proposed by Broadbent and Hammersley,[10] can be used to simulate the filling or emptying of a fracture for a variety of conditions. In these approaches, the fracture aperture geometry is simplified and modeled by a two-dimensional checkerboard of aperture elements. Aperture fields are created by assigning each element a single aperture value selected from the appropriate distribution. Hydraulic properties of the aperture field may be systematically varied through both the aperture distribution and the spatial correlation function used to assign apertures within the plane. Currently, we use a beta distribution to generate the aperture distribution because it allows definition of a maximum and minimum aperture value with a wide selection of functional behavior.[11] Three models are used to simulate spatial structure within the fracture aperture plane: random spatial structure; fractal spatial structure[12]; and spatially correlated structure.[13]

TABLE 1: SYSTEM PARAMETERS, INITIAL/BOUNDARY CONDITIONS

1. Physical properties of the fracture
   a. mean topography of roughness/aperture (microscopic length scale)
   b. roughness/aperture distribution about the mean
   c. spatial structure of aperture within fracture plane
   d. distance between fracture walls
   e. micro-fractures or micro-porosity at fracture walls

2. Fluid properties
   a. surface tension
   b. viscosity
   c. density
   d. contact angle between liquid, gas, and fracture wall (wettability)

3. Composite hydraulic and transport properties of the matrix
   a. relative permeability
   b. fluid characteristic relation
   c. solute dispersivity

4. Macroscopic geometry of fracture/matrix flow system
   a. macroscopic length scale
   b. orientation in gravity field

5. Initial/boundary conditions of fracture/matrix system
   a. initial saturation
   b. flux or pressure supplied to the matrix
   c. open or closed fracture edge boundaries

To simulate water entry into a fracture from the matrix, we will initially explore four types of percolation models: 1) standard percolation (SP), 2) standard percolation with trapping (SPT), 3) invasion percolation (IP) instigated from matrix-matrix contact points, and 4) invasion percolation with trapping (IPT).

The SP process simply ranks each aperture according to its filling potential p_f, defined by the pressure-head jump across the curved fluid-fluid interface within the aperture. The Laplace-Young equation relates p_f to the surface tension σ, contact angle α, and fluid-fluid interfacial curvature (given by 2/a where a is the aperture) as

$$p_f = -(2\ \sigma \cos(\alpha))/(\rho\ g\ a) \qquad (1)$$

where g is the acceleration due to gravity and ρ is the fluid density. Note that Equation (1) neglects any curvature in the plane of the fracture. The process then sequentially fills apertures up to a given potential in order from lowest potential to highest. SP conforms to the distribution of fluid within a fracture under thermodynamic equilibrium. That is, all apertures are in a state of mutual communication. Three communication processes exist: 1) flow through the matrix which connects all apertures, 2) film flow along the fracture walls and, 3) diffusion processes. Thus, for SP to be applicable to an unsaturated fracture within a porous matrix, we must be simulating fracture filling on time scales long with respect to that of the fastest communication process.

IP models a process in which the pressure potential within each fluid does not vary in space and the filling of apertures is done sequentially from a designated boundary or initiation point.[14] This is a reasonable assumption in the limit of infinitesimal flow rate where viscous forces are negligible and the system is dominated by capillary forces. Application requires communication processes other than through the wetted fracture structure to either not exist or displacement to take place on a time scale that is small compared to existing communication processes. For our problem, flow is initiated at matrix-matrix contact points and grows outward from each point.

If the matrix on both sides of the fracture is wet, as is expected under near quasi-atatic conditions, air will not be able to eacape through the oppoaite aide of the matrix once it is surrounded in the fracture except through dissolution. To include these air entrapment effects, SP and IP models are modified to include trapping procedures, SPT and IPT respectively. The trapping procedure keeps treck of the connection of pores filled with air to an open boundary. When water fills an aperture that cuts this connection for other air-filled apertures, they become entrapped and are no longer accessible for water entry. Such a trapping rule assumes the air to be incompressible. This assumption can be removed by using the ideal gas law to allow some additional water to penetrate the entrapped air zone as a function of pressure. Trapping alters the final state substantially and creates a "satiated" value of the saturation at zero pressure head. IPT is essentially a simplified form of the pore-scale models developed in the petroleum engineering field.[15,16] SPT was first explored by Dias and Wilkinsen.[17]

Numerical procedures for SP and IP/IPT for imbibition from the fracture edge have been implemented. Numerical procedures for SPT and IP/IPT instigated from contact points have not been considered in the literature and will be implemented as our investigation progresses. Modifications in these models to include gravity effects and interface smoothing functions which address interfacial curvature in the fracture plane such as presented by Glass and Yarrington[18] also may be required to predict wetted-area structure.

Many general results of SP, SPT, IP, and IPT, primarily on spatially random two-dimensional networks, may be found in the literature. We make use of these results in the discussion of our preliminary physical experiment below.

Physical Experimentation

Our physical experimentation isolates the wetted-structure within the plane of a horizontal fracture for investigation as a function of matrix pressure head and fracture physical properties. The key to this experimentation is to replace the matrix block on one side of the fracture with a transparent plate so that water-filled aperture structure can be visually recorded as a function of pressure head. Since the transparent plate is impermeable and creates a no-flow boundary, the experimental system simulates a half-plane fracture-matrix system, i.e., matrix properties and pressure states on one side of the fracture are the mirror image of the other side.

Three types of analogue fracture/matrix systems have been designed to maximize experimental control and resolve the wetted-region structure within the fracture in detail. In all systems a thin (approximately 1 cm), extensive (10x15 cm and larger) matrix is mated with a transparent fracture plate. Aperture fields are obtained by profiling the matrix and transparent fracture plate using a laser profilometer.

The first system mates a smooth-surfaced matrix plate of sintered glass beads with a rough-sided commercially available obscure glass. Matrix properties are controlled through bead size distribution and the time and temperature of the sintering process (the greater the time and temperature, the greater the consolidation and thus the smaller the pores and porosity). Three macro-roughnesses in the obscure glass have been obtained. Two different sands, fine and coarse, may be used to sand blast the surfaces and impart micro-roughness. Sand blasting in combination with the three macro-roughnesses yields 9 different aperture distributions/spatial structures for consideration. While aperture fields can be varied qualitatively with this system, systematic exploration of aperture distribution/spatial structure is not possible.

The second system uses a naturally occurring fracture. We replace the matrix on one side of the fracture with a replica in clear epoxy, thus preserving the natural fracture aperture field while allowing measurement of wetted-region structure. This system allows us to explore a variety of naturally occurring fractures (such as cooling or tectonic fractures), constrained only by our ability to collect undamaged samples of large size. However, two drawbacks remain: first, some small-scale detail is lost or changed in the casting process; and second, heterogeneities in the natural matrix pose difficulties in imposing quasi-static conditions. In addition, systematic exploration of aperture distribution/spatial structure is still not possible.

The third system allows systematic exploration of aperture distribution/spatial structure by manufacturing fractures to specification. A given set of two surfaces defining the fracture are milled into blocks of graphite, forming a mold in which we cast the manufactured fracture. One side is cast in transparent glass and the other side is used to sinter glass beads forming the porous matrix. Preliminary work in fracture fabrication has used a fractal model[12] to generate the two fracture surfaces at a spatial resolution of 0.2 mm in the fracture plane which are milled with a resolution of 0.0025 mm normal to the fracture plane. In order to vary matrix and fracture properties systematically, Miller and Miller[19] scaling theory will be applied to design the combined fracture/matrix system.

At this stage in our research, we constrain matrix properties and fracture properties for all three model fracture systems such that the pores in the matrix are always smaller than the apertures in the fracture. This removes the bulk matrix capillary properties from consideration because the matrix always will be fully saturated during a test. Also, if we consider only quasi-static conditions, heterogeneity within the matrix is irrelevant. Thus, we simulate the slow filling and emptying of an unsaturated fracture within a saturated matrix where water is in a state of tension and air can escape only through the fracture edge.

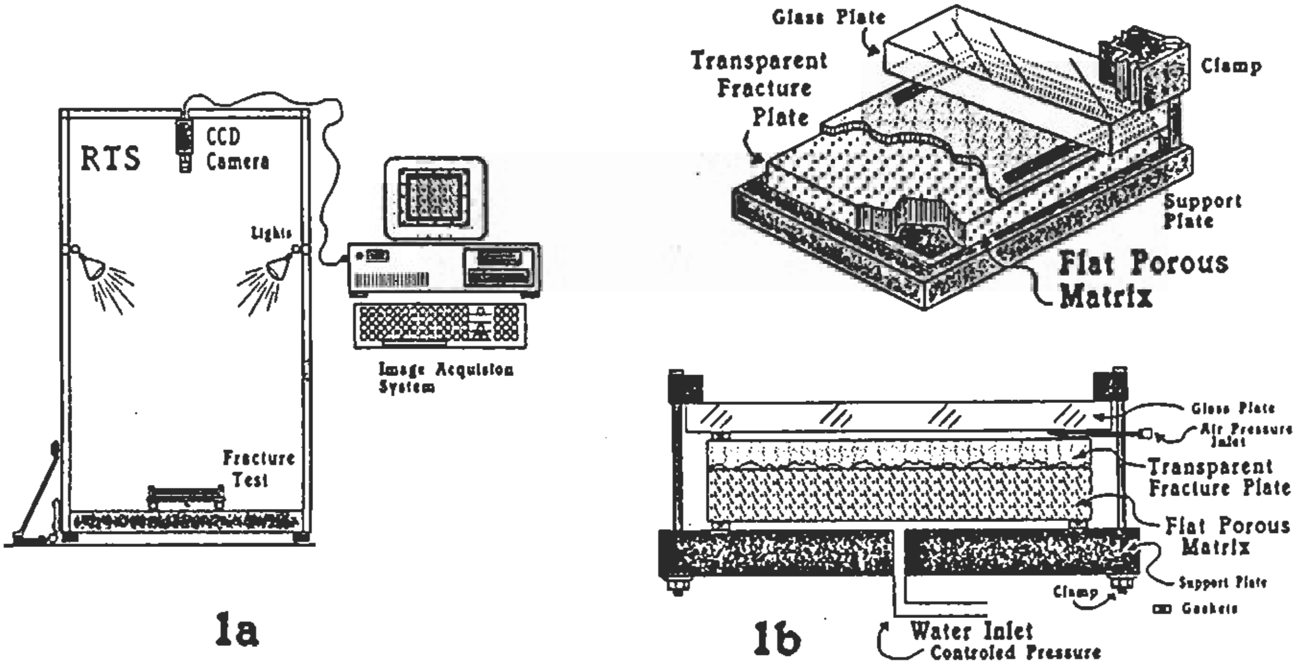

Fig. 1: Drawing of experimental system composed of the rotating test stand (RTS), the fracture-matrix test cell and the image acquisition system. 1a) The RTS is a rectangular eight-foot-high steel framework box that holds the components of the image acquisition subsystem (video camera and lighting) and the fracture/matrix test cell. 1b) The fracture-matrix test cell is composed of two parts: the porous matrix back plate and the transparent/impermeable fracture plate. The matrix plate is sealed to a gasket on the bottom outer plate over a port through which water enters the system at prescribed pressure. The aperture structure plate is sealed to a gasket on the top outer transparent plate. The gap between the top outer plate and the fracture aperture plate is pressurized after assembly to force the matrix and fracture plates together and eliminate long wavelength aperture disturbances.

PRELIMINARY PHYSICAL EXPERIMENTATION

As a proof of concept for our physical experimentation, we designed and conducted a preliminary experiment. The experiment tested our model fracture design and developed our data acquisition and reduction procedures. To the authors' knowledge, it also demonstrates fracture wetted-structure behavior, when wetted from the matrix, for the first time.

Experimental System Design

The experimental system is designed to make use of reflected light visualization techniques that allow digital image acquisition and analysis. The system consists of three major parts: the rotating test stand (RTS), the fracture/matrix test cell, and the image acquisition system.

The RTS is a rectangular, eight-foot-high steel framework box that holds the components of the image acquisition subsystem (video camera and lighting) and the fracture/matrix test cell (Figure 1a). The RTS is rigidly constructed so that the angle of the test plane with respect to vertical can be changed during the course of an experiment while maintaining camera/test cell alignment. (This feature will be used in future studies.)

The general fracture/matrix cell design (Figure 1b) can be broken down into two parts: the porous matrix/backing plate and the transparent/impermeable fracture plate. The matrix plate is sealed to a gasket on the bottom containment plate over a port through which water enters the system at prescribed pressure. The analogue fracture plate is sealed to a gasket on the top containment transparent plate (3/4" glass). The gap between the top containment plate and the fracture aperture plate is pressurized after assembly to force the fracture and matrix plates together and eliminate long wavelength aperture disturbances.

The lighting for the image acquisition system consists of four fluorescent bulbs driven

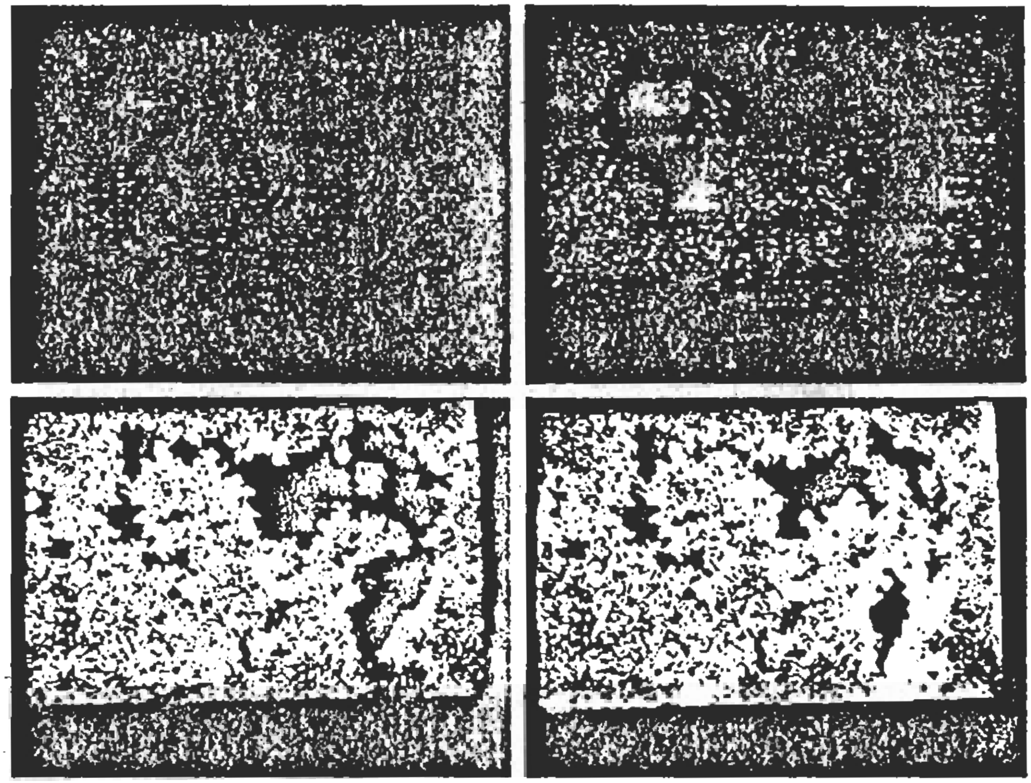

Fig. 2: Images taken of physical experiment showing wetted area structure as a function of pressure head for wetting cycle: top left, -155 mm; top right, -93 mm; bottom left, -53 mm; bottom right, 0 mm; water-filled regions are light, air filled regions are dark.

by a high-frequency ballast (40 kHz). This ballast eliminates sixty hertz flickering while the camera acquires images. The camera chosen for image capture, a monochrome COHU 4800 Series Solid State Camera, is routinely used in security and machine vision applications. Camera signal is digitized by a DATA TRANSLATION 2862 frame grabber through an IBM-AT computer bus. The frame grabber digitizes the video signal into 512x512 pixels per image with 256 gray levels per pixel.

Preliminary Physical Experiment

A preliminary experiment was conducted using the first type of analogue fracture/matrix system. A 10x15x0.5 cm block of sintered beads formed the smooth porous matrix and was mated with a fracture plate composed of one of the obscure glass types sandblasted with coarse sand. The fracture and matrix plates were forced together at 20 psi. Blue-red USDA food coloring (2 gms/liter of deionized water) was used to increase visual contrast for image acquisition. The addition of the food coloring was not found to affect capillary properties of the fracture/matrix system. We performed two fracture wetting-drying cycles starting from an initially dry condition in the fracture and a fully saturated matrix. Fracture edges were open to atmospheric pressure.

Results

Figures 2 and 3 show the wetted area structure as a function of pressure head for the second wetting and drying cycle, respectively. Analysis of the images to determine the number of pixels spanning the aperture and thus area or saturation at each pressure head yields the results shown in Figure 4. Hysteresis in the saturation-pressure head relation is clearly evident. It is also clear from the figures that air entrapment limits total saturation to 60%.

Our experiment shows that, once the system is spanned, there is very little change in wetted or entrapped region structure. This rapid

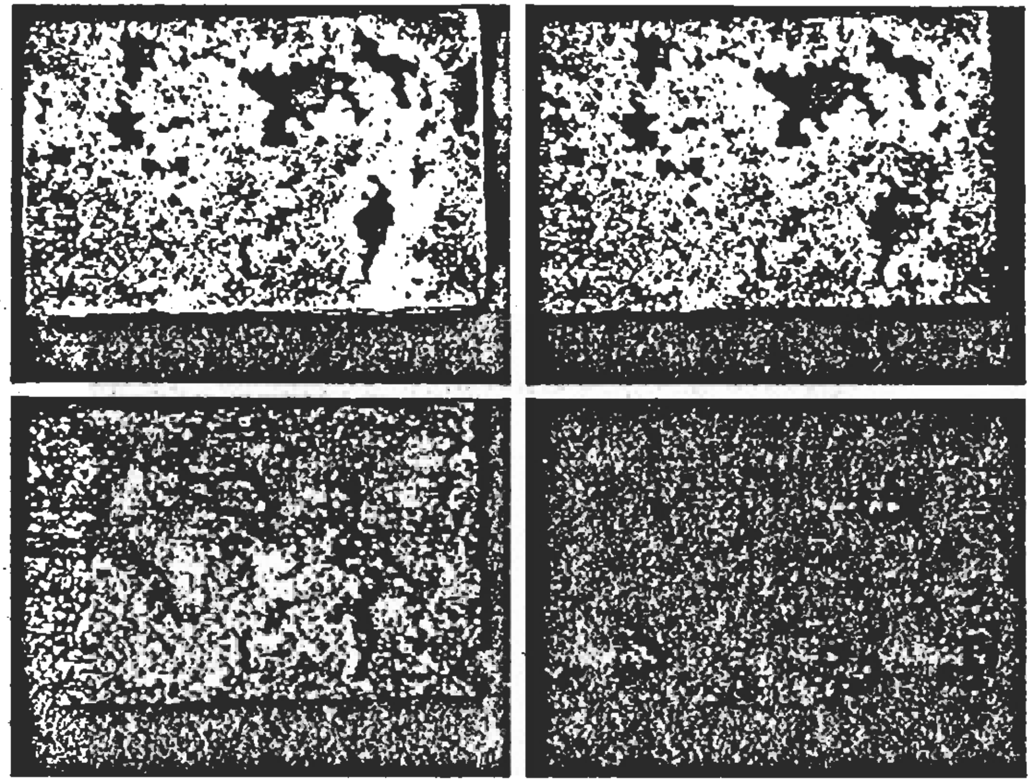

Fig. 3: Images taken of physical experiment showing wetted area structure as a function of pressure head for drainage cycle: top left, 0 mm; top right, -190 mm; bottom left, -208 mm; bottom right, -264 mm; water-filled regions are light, air filled regions are dark.

spanning of the aperture field accompanied by significant air entrapment is analogous to percolation threshold behavior in SPT and IPT models. The critical threshold pressure head p_c, is defined as the pressure head where the system is first or last spanned, for wetting and drainage respectively. Approximate values for these points are circled in Figure 4.

The final (0 mm pressure-head) wetted-structures shown in Figures 2 and 3 are complicated at all scales up to the size of the experiment. In addition, the size of the entrapped zones range from very small to nearly the size of the experiment. The intuitively fractal character of the wetted structure will be investigated in the future.

DISCUSSION

The results of our preliminary experiment and relevant results from aperture-scale percolation models yield implications for in-plane fracture flow, inter-block fluid transfer, and the definition of effective-media properties. These implications are considered to be preliminary; they provide hypotheses to be tested through systematic physical and numerical experimentation in our future research.

Implications of Percolation Threshold Behavior for the Onset of In-Plane Fracture Flow

A fracture can only conduct water in its plane after it is spanned at p_c by a connected "percolating" cluster. At p_c the backbone of the percolation cluster is the only relevant path for conduction.[20] Thus, the permeability, K, will jump from 0 to the backbone permeability at p_c (K_{pc}). Between p_c and the final 0-mm pressure head state, K will continue to increase up to the fully saturated permeability, K_s, if there is no trapping. A model embodying this process on a spatially correlated aperture field was used by Pruess and Tsang[13] to calculate moisture-characteristic and relative-permeability relations for a simulated fracture.

It is clear that models that do not include trapping have application only where thermodynamic considerations dictate that entrapped regions will dissolve entirely. Kinetics of the dissolution process restrict application to time scales long with respect to that of dissolution. When this is not the case, trapping, such as that observed in our experiment and IPT model simulations, will influence fracture permeability. While K_{pc} will be reduced only slightly, the permeability in the final trapped state, K_t, will be significantly reduced from K_s. Our experiment suggests a sharp transition from 0 permeability to K_{pc} with very little increase to K_t. Relative permeability functions, therefore, may be very sharp and possibly should be modeled as step functions.

Note that if p_c is found to be independent of scale (as suggested by all forms of percolation theory), then the threshold pressure head characterizing the crossover between nonconducting and conducting will be a function only of the aperture corresponding to p_c. P_c, however, will display hysteretic behavior as seen in Figure 4.

Implications of Wetted Structure

For a random aperture structure, percolation theory (all forms) suggests the wetted structure to be fractal at p_c with the number of apertures filled, N, a function of the maximum length of the system, L, following the general power law form

$$N(L) = A\ L^D \qquad (2)$$

where A is a constant of proportionality and D is the fractal dimension. Saturation $[N(L)/L^2]$ also follows a power-law dependence on L. The size distribution of entrapped clusters also has been found to obey a power law.[17]

The in-plane tortuosity, and thus the values of K_{pc}, K_t, relative permeability, and the dispersivity, will be a function of the wetted structure. If the results from percolation theory hold for rough-walled fractures, tortuosity in the fracture plane, and thus fracture permeability and dispersivity, also will be a function of scale (even within a random aperture field).

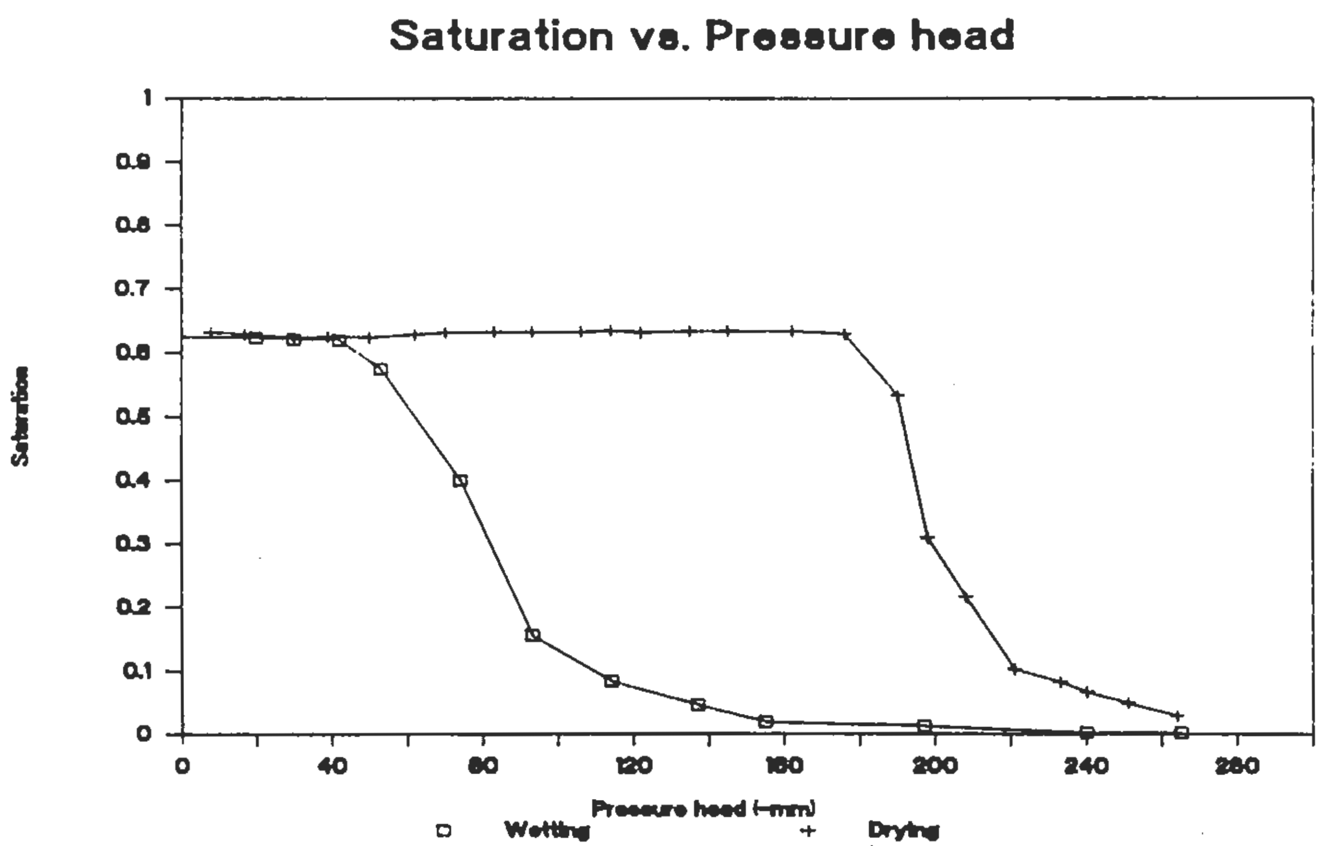

Fig. 4: Saturation as a function of pressure head measured for wetting cycle (Fig. 3) and drying cycle (Fig. 4). Hysteresis in the saturation vs pressure head relation is clearly demonstrated. Circles denote the threshold pressure when the fracture is first and last spanned by water for wetting and drainage, respectively.

Wetted structure also determines inter-block communication. A fractal structure for inter-block connection will have a significant effect on tortuosity for inter-block fluid and solute transfer. The power-law relation for saturation (inter-block connection) shows the area of connection to decrease as a function of scale. Where entrapped regions do not dissolve, they may form a fractal disconnect structure at satiation (0-mm pressure head). Thus, simple models that predict total saturation and no regions of disconnect will be incorrect. If these results prove true for rough-walled fractures, inter-block fluid-transfer tortuosity will be a scale-dependent function of pressure head.

Implications for Effective-Media Properties

Wetted-area structure and air entrapment will play very little role in modifying effective-media moisture characteristic curves because the relative volume of entrapped air will be small. The effect on steady-state flow fields, however, will be significant.

Neglecting gravity effects on fracture wetted structure within a fractured rock formation and assuming all fractures to have identical p_c values, fractures will increase the flow tortuosity within the formation above that measured from matrix property variability under all steady flow situations up to p_c. If no trapping occurs, then flow tortuosity will decrease to the value determined by the matrix variability and saturated fracture network for pressure heads between p_c and p_s (value of pressure head for largest aperture) as the fractures begin to conduct flow in their planes and increase inter-block connection. If trapping occurs, then the tortuosity will not substantially decrease beyond that at p_c, because the wetted structure within a wetted fracture will change very little. Thus, effective permeability will be significantly lower than assumed by simple composite-media models, such as that proposed by Peters and Klavetter,[21] for almost all situations at all pressure heads. Likewise, effective dispersivity will be significantly increased.

A critical point for effective-media properties is the transition from matrix-dominated to fracture-dominated flow. For a network of variable fractures, each individual fracture will begin to conduct in its plane when its p_c is realized. However, the entire fracture network is not spanned until the network threshold pressure head is realized. Therefore, zones of fracture flow within a rock formation may be of limited size until p_c for the entire network is reached.

In addition to these points, gravity effects on fracture wetted-structure cannot be neglected for fractures larger than L, approximately given by

$$L = - p_c / \sin(\theta) \qquad (3)$$

where θ is the angle with respect to horizontal. Inclusion of gravity effects on wetted structure will allow non-horizontal fractures to conduct fluid in their planes down the gravity potential gradient at pressures well below p_c. Current research on gravity effects and gravity-driven fingers is reported by Nicholl and Glass.[9] Incorporation of gravity effects into rock-formation-scale effective properties promises to be a challenging problem.

CONCLUSION

Our research on wetted-region structure integrates aperture-scale modeling and physical experimentation to investigate small-scale hydraulic processes in the plane of an unsaturated horizontal fracture. Four types of aperture-scale models have been defined and we are implementing their numerical solution. A series of physical experimental systems that allow us to measure wetted-region structure as a function of system parameters and water pressure head also have been designed and a preliminary experiment has been conducted.

In our preliminary experiment, hysteresis is clearly evident in the measured saturation/pressure relation. Air entrapment is also evident, causing a reduction in the connected areas between blocks (40% in our experiment) and area for in-plane fracture flow. A percolation threshold at which the system is quickly spanned, allowing fluid conduction along the fracture plane, is observed that is analogous to that found in the aperture-scale models. A fractal wetted structure is suggested by both experiment and modeling. This structure implies flow tortuosity, both for flow in the fracture and for inter-block fluid transfer, to be a scale-dependent function of pressure head.

From these results, we posit that the understanding of wetted structure and the processes that create it is critical for defining the onset of flow within a fracture, in-plane fracture relative permeability, and inter-block fluid transfer. Knowledge of these effects is necessary to define defensible large-scale effective-media properties. Only through continued systematic physical experimentation and aperture-scale modeling can this understanding be built.

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